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INFLUENCE OF LIFT AND CRUISE ENGINE DESIGN ON THE TRANSITION CHARACTERISTICS AND GROUND ACOUSTIC FIELD OF VTOL TRANSPORT AIRCRAFT

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TERISTICS AND GROUND ACOUSTIC FIELD OF VTOL TRANSPORT AIRCRAFT

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ABSTRACT. A transition technique for maximum horizontal ac-
celeration is used to evaluate the influence of engine design
and thrust-vector control on the transition characteristics.
It is shown that the vertical balance of forces in transition,
and hence the transition characteristics, are influenced dir-
ectly by the input-output impulse ratio and by the thrust-
vector control characteristics of the lift and cruising en-
gines, and indirectly by optimal adaptation of the cruising
engines to the cruising flight requirements and by the number
of lift and cruising engines installed. A parametric analysis
of mixed and direct lift configurations shows that thrust-
vector control over an angle of at least 30 deg for the lift
engines is essential for ensuring safe transition.

1. Introduction and Problem Definition

Since in the case of VTOL and STOL aircraft the selection and design /1*
of engine systems are of decisive importance, the present paper will analyze
the specific effect of lift and cruise engine design on transition behavior
and ground acoustic field in order to derive certain recommendations con-
cerning the choice and design of engine systems.

VTOL aircraft with a takeoff weight of approximately 52 t were selected
as reference aircraft for the investigation; the engine systems of these air-
craft can be varied over a large range with respect to number of engines, by-
pass ratio and thrust angles of the lift and cruise engines. Specifically,
a configuration with a fully rotatable thrust vector of the cruise engine
(mixed lift configuration) is compared with an aircraft with a cruise engine
thrust that cannot be rotated or deflected (direct lift configuration). In
addition, within a certain range the effect of wing loads and the flap system
is to be included in the investigation.

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*Numbers in the margin indicate pagination in the foreign text.

Initially, the engine parameters affecting the horizontal and vertical force equilibrium will be determined qualitatively by dimensioning the engine during the transition; later, parametric studies will be used to determine their influence qualitatively. In order to make the unambiguous correlation of control values affecting the transition, such as engine thrust angle, flight attitude or attack angle, and also the vertical velocity and acceleration components possible, a transition profile with constant altitude and maximum horizontal acceleration is used and the process briefly explained.

For the determination of the ground acoustic field, the transition profile for rising flight paths for engine systems planned for the period of 1975/80 is established so that a minimum noise effect may be expected under the prevailing conditions. In addition, direct operating costs per seat-km are estimated for such a flight profile and compared with costs for a ground-vicinity profile.

2. Transition at Constant Altitude with Optimum Choice of Angles of Attack and Thrust Control

In addition to the effect of lift and cruise engine design, aerodynamic design, and aircraft configuration, to be specifically investigated here, the transition process is determined by the following factors:

angle of rotation of the thrust vector of the cruise engine, σ;
angle of rotation of the thrust vector of the lift angle, ϵ;
rate of rotation of the thrust vectors, $d\sigma/dt$; $d\epsilon/dt$;
attitude angle of the aircraft or angle of attack, ϑ, α;
wing flap angle, η_k;
initial vertical velocity, $v_v = dh/dt$;
initial vertical acceleration, $b_v = d^2h/dt^2$.

While observing safety rules and the requirements of attitude control, different transition processes can be established by varying the aforementioned factors. Since no guidelines have been issued by the air traffic authorities for the starting and landing procedures of civil VTOL traffic aircraft, and in order to define the correlation of the factors as closely as possible for the purposes of the investigation of engine parameters, a theoretically optimum transition process was chosen for the investigation, which yields maximum horizontal acceleration and thus minimum values of time,

consumption and distance, at constant flight altitude (detailed description in [1, 2]). A method suitable for comparative considerations is thus defined, which (as will be shown) leads to correct trends and comparable results in comparison with actual use profiles.

The entire process from start to aerodynamical flight is performed in the following sections (Figure 1):

Phase I   Vertical rise to a predetermined transition altitude;

Phase II   Transition at constant altitude ($dh/dt = 0$) through the simultaneous rotation of the cruise and lift thrust vector to a maximum deflection angle ϵ_{max} of the lift vector;

Phase III Additional rotation of the cruise thrust vector to a minimum value of σ_{min} at constant ϵ_{max};

Phase IV   Suitable throttling of the lift thrust with increasing flight velocity at constant altitude and constant engine rotation angles σ_{min} and ϵ_{max}.
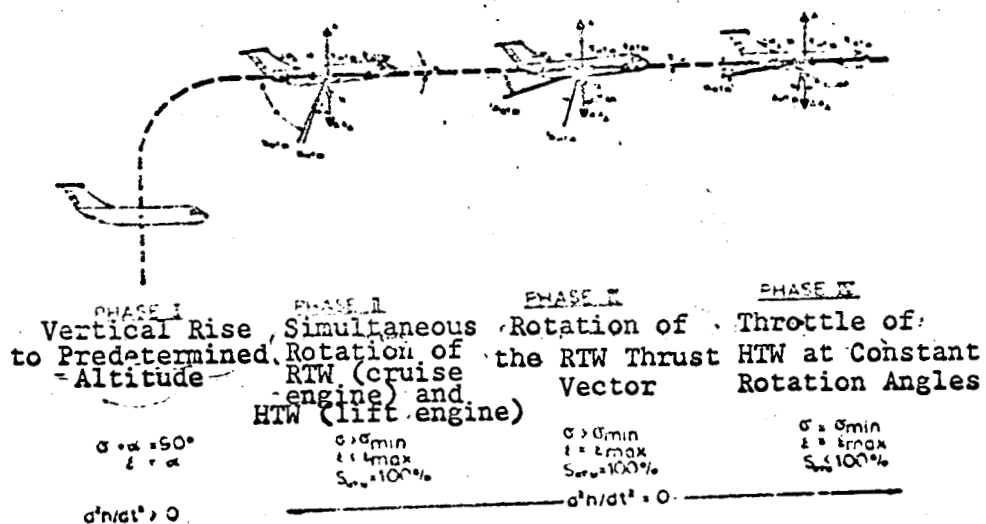

Figure 1. Transition at Constant Altitude
Optimum Choice of Attack and Engine
Thrust Rotation Angles

In Phases II to IV (Figure 2), the angle of attack α and the angle of rotation of the lift and cruise vectors σ and ϵ (Phases II and III) are

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varied for the step-like given air velocity v∞ and the optimum combination of these parameters calculated for maximum horizontal acceleration. The given flight velocity v_∞ is varied gradually. In Phase IV, the angle of attack and the degree of throttle of the lift engine are correlated under similar conditions.

Let us terminate the transition in accordance with FAA requirements for HTOL aircraft at

$$V_{aero} = 1.2 \times V_{min} \qquad (1)$$

After this velocity has been attained, the cruise flight configuration is assumed, i.e., the lift engines are turned off and the lift engine flaps closed; the landing gear and the landing flaps are retracted.

Time, fuel consumption and distance can then be determined by integrating the maximum horizontal acceleration between the initial and final velocity of the transition.
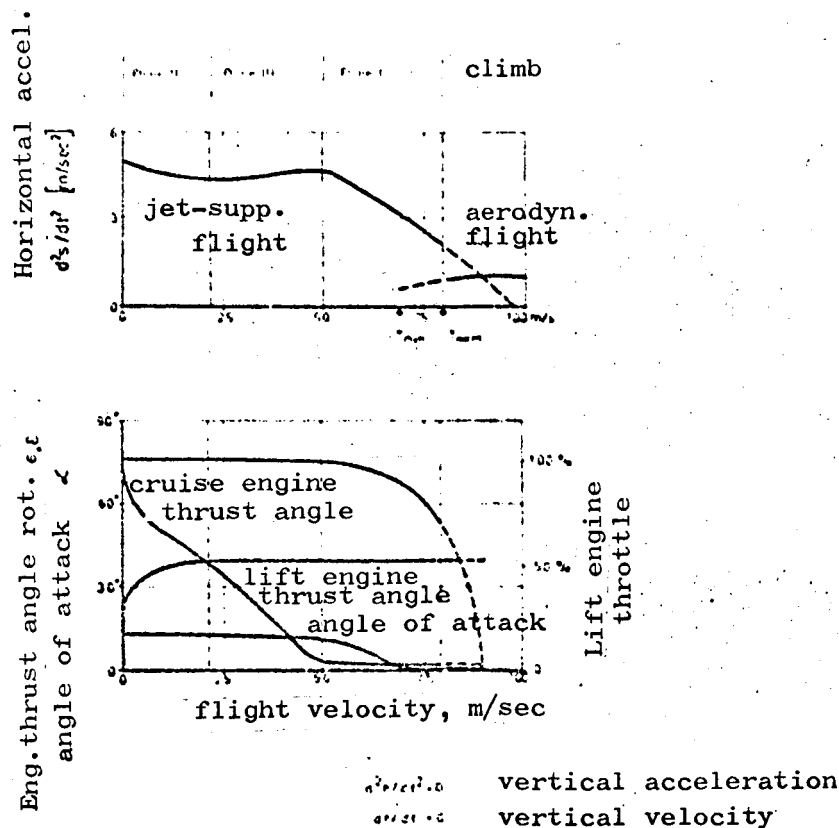
Figure 2. Transition Processes - Transition at Constant Height.

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In order to maintain the momentum equilibrium around the center of gravity, aerodynamic control forces and control thrusts must be applied during the transition, for which an average value was deducted in the thrust balance so that in the following the configuration investigated here may be considered point masses.

3. Engine Design

In the design of the engines primarily a variation of the by-pass ratio is performed, because in addition to the thrust distribution in lift and cruise propulsions and the angle of thrust rotation, this has the greatest effect on transition.

3.1. By-Pass Ratio

Transition performance (time, distance and fuel consumption) is first affected directly by the by-pass ratio of the lift and cruise engines selected, because the input pulse force of the engines acting against the flight direction enters the horizontal force balance negatively, i.e., as a resistance (see Figure 1), and the ratio of the input/output $(\dot{J}_E/\dot{J}_A)$ increases with rising by-pass ratios and flight Mach numbers. As an example, Figure 3 shows the $(\dot{J}_E/\dot{J}_A)_{HTW}$ ratio of the lift engine as a function of the by-pass ratio and the Mach number. Cruise engines behave in an analogous manner.
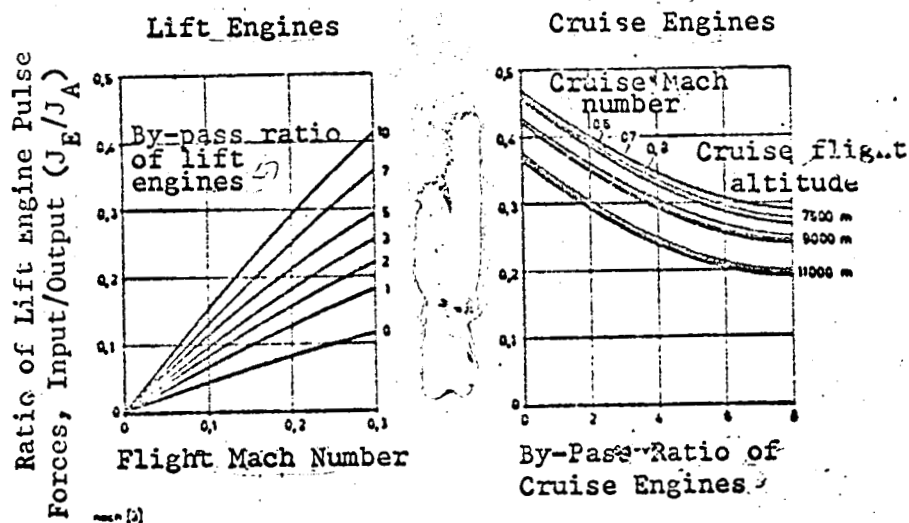

Figure 3. Effect of By-Pass Ratio on Engine Performance

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It will be shown that transition characteristics are strongly and indirectly affected, in addition to the aerodynamic design and the rotatability of thrust vectors, by the distribution of the thrust between lift and cruise engines and thus by the dimensions of the cruise engines, the installed net take-off thrust and the number of propulsion units. In order to demonstrate this functional relationship, the dimensioning of engines will be discussed in the following sections.

3.2. Dimensioning of Cruise Engines

Cruise engines are adapted in an optimum manner to cruise flight conditions and in certain cases used to support the take-off thrust through rotation or suitable deflection systems.

In the adaptation of cruise engines to cruise flight conditions, the following values determine the thrust of the cruise engine on the stand:

cruise flight requirements,	M_R, H_R;
size of aircraft,	G_A, c_{Wo};
aircraft design,	G_A/F;
thrust ratio of the cruise engine,	$s = S_{cruise}/S_{stand}$;
loss of thrust due to inlet pressure drop, diversion of air and deflection systems in cruise flight	K_R.

From the cruise polar coordinates (depending on cruise flight altitude and Mach number):

$$C_{AR} = \frac{G_A/F}{(\rho/2 \, a_\omega^2) \cdot M_R^2} \tag{2}$$

$$C_{WR} = C_{Wo_{M_R}} + \frac{K}{\pi \cdot \Lambda} \cdot C_{AR}^2 \tag{3}$$

the total gross stand thrust of the cruise engines can be calculated.

$$S_{o_{ges.}}^{RTW} = \frac{C_{WR} \cdot G_A}{C_{AR} \cdot K_R \cdot s} \tag{4}$$

The functional relationship of the thrust ratio cruise thrust/stand thrust shown in Figure 3 indicates that with increasing cruise altitudes and Mach numbers and rising by-pass ratios the stand thrust of cruise engines also increases.

As a result, the following relationship is found for the gross stand thrust of cruise engines:

$$S_{o_{ges.}}^{RTW} = f (\mu_{RTW}, H_R, M_R, G_A, G_A / F)$$ (5)

3.3. Net Take-Off Thrust Required for Vertical Take-Off

It is necessary for a vertically starting transport aircraft that, following the failure of an engine and the possible cut-off of another symmetrically arranged engine, an excess thrust $\Delta S '/G_A$ or at least a hovering capability be retained. For such cases, the engine manufacturers offer certain emergency lift reserve ΔS_{Not} up to 10% of the standard take-off a thrust, by which the take-off thrust can be temporarily increased in an emergency. /7

In addition, in accordance with AGARD standards, the controllability of the aircraft must also be maintained in the case of the failure of an engine. In the vertical thrust balance, therefore, the thrust required for control purposes must be taken into account as the necessary excess thrust $(\Delta S/G_A)_{Steu}$.

Mixed Lift Configuration

In a mixed lift configuration, the thrust of the cruise engines is used in vertical take-offs and in transition, through thrust angle rotation. Because in such a case the thrust of the cruise engines, designed in accordance with cruise requirements, generally will not be equal to the lift thrust, in the determination of the necessary excess thrust the failure of the engine with the greatest thrust must be considered.

If z is the number of engines failed or cut off for reasons of torque equilibrium, and n_{HTW} and n_{RTW} are the numbers of lift and cruise engines installed with a net thrust of S_N^{HTW} and $_N^{RTW}$, the necessary net take-off thrust is given by:

$$\frac{S_{N\,ges}}{G_A} = \frac{1 + \Delta S/G_A + (\Delta S/G_A)_{Steu}}{(1 + \Delta S_{Not}/S_N)\left[1 - z \cdot S_x/(n_{HTW} \cdot S_N^{HTW} + n_{RTW} \cdot S_N^{RTW})\right]} \qquad (6)$$

$$S_x = S_N^{RTW} \quad \text{für } S_N^{RTW} > S_N^{HTW}$$

$$S_x = S_N^{HTW} \quad \text{für } S_N^{RTW} < S_N^{HTW}$$

For lift and cruise engines with unequal thrust, where the latter is designed for flight Mach numbers of 0.8 at an altitude of 7,500 m, the required net take-off thrust is shown in Figure 4 as a function of the installed lift engines and of the by-pass ratio of the cruise engines. The necessary excess thrust is therefore determined, in addition to the number of lift and cruise engines, by the by-pass ratio of the cruise engines, which controls their stand thrust at given flight conditions [see Equation (5)].
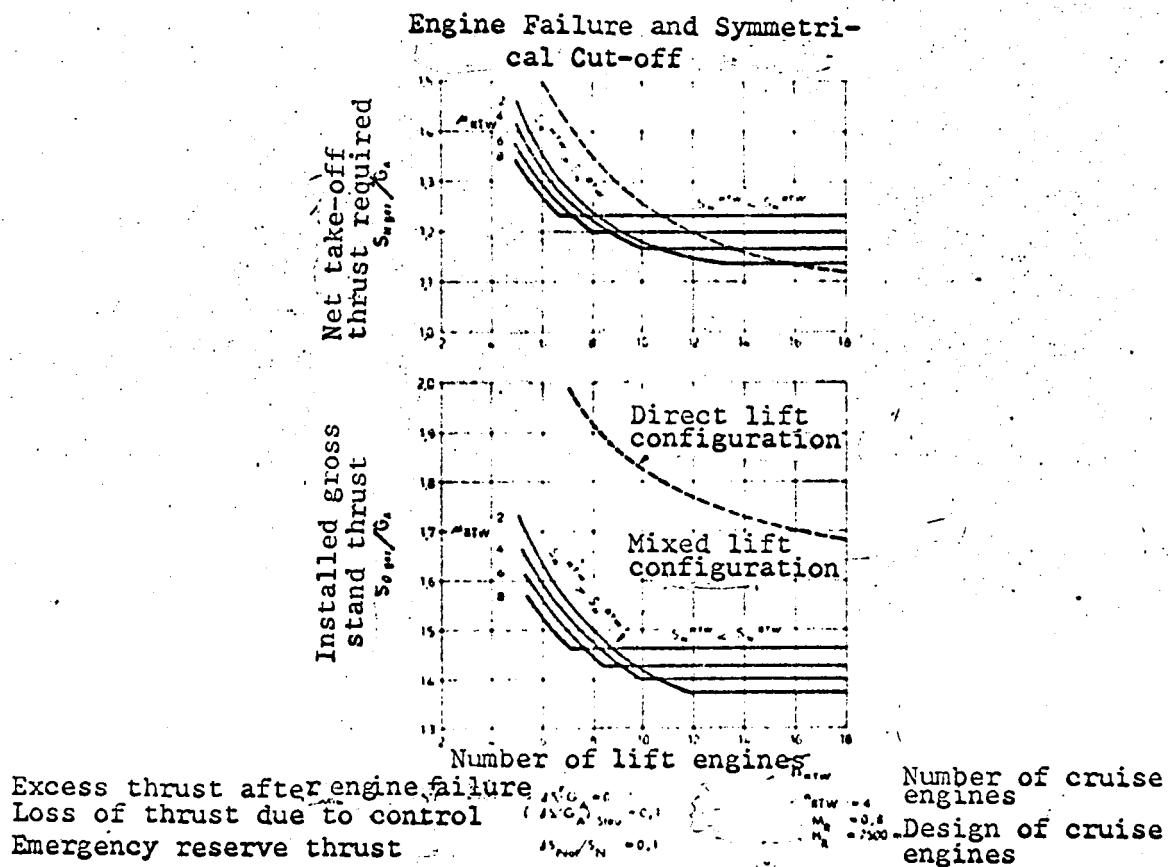

Figure 4. Dimensioning of Engines –
Effect of Number of Lift Engines and
By-Pass Ratio of Cruise Engines

If the net thrust of lift engines is decisive in the case of engine failure, then the difference in the net take-off thrust between by-pass ratios of 0 and 8 of the cruise engines can amount to 35%, because the by-pass ratio of the cruise engines also determines the thrust class of the lift engines (see Section 3.4.).

If the failure of cruise engines becomes the decisive factor ($S_N^{RTW} > S_N^{HTW}$), then an increase in the number of lift engines has no effect on the excess thrust which remains constant. The number and the by-pass ratio of the cruise engines, on the other hand, increases in importance.

With consideration of Equation (5), the following relationship can be established for the net take-off thrust:

$$\frac{S_{Nges}}{G_A} = f\left(\mu_{HTW}, \mu_{RTW}, S_N^{HTW}, S_N^{RTW}\right) \qquad (7)$$

Direct Lift Configuration

In direct lift configurations the thrust vector of cruise engines is not used during vertical take-off. Only the thrust of the lift engines is thus decisive in the vertical balance of forces.

In this case

$$S_x = S_N^{HTW} \qquad \text{and}$$

$$n_{RTW} = 0$$

so that Equation (6) becomes

$$\frac{S_{N\,ges}}{G_A} = \frac{1 + \Delta S/G_A + (\Delta S/G_A)_{Steu}}{1 + \Delta S_{Not}/S_N} \cdot \frac{n_{HTW}}{n_{HTW} - z} \qquad (8)$$

As shown in Figure 4, in this case the take-off thrust required depends on the number of lift engines only.

The total installed net stand thrust given additionally contains the stand thrust of the cruise engines which become effective during the transition only.

3.4. The Dimensioning of Lift Engines

With consideration of the necessary net take-off thrust determined in Section 3.3., the net thrust required for safe take-off is given by

$$S_N^{VTO} = G_A \cdot \frac{S_{Nges.}}{G_A} \qquad\qquad (9)$$

If the thrust of the cruise engines cannot be made available for the
vertical force balance (direct lift configuration), then the gross stand
thrust of the lift engines must be determined, with consideration of the in-
stallation losses (K_{HTW}), corresponding to Equation (9)

$$S_{o_{ges}}^{HTW} = \frac{S_{Nges}}{G_A} \cdot \frac{G_A}{K_{HTW}} \qquad\qquad (10)$$
$$\text{(direct lift configuration)}$$

Diversion of the cruise engine thrust (mixed lift configuration) reduces
the lift engine thrust required corrdspondingly, so that the gross stand
thrust can be determined from

$$S_{o\,ges.}^{HTW} = \frac{S_{Nges.}}{G_A} \cdot \frac{G_A}{K_{HTW}} - \frac{K_{RTW}}{K_{HTW}} \cdot S_{o_{ges}}^{RTW} \qquad\qquad (11)$$
$$\text{(mixed lift configuration)}$$

The following relationship is then valid for the gross stand thrust of
the lift engines

$$S_{o_{ges}}^{HTW} = f\left(\frac{S_{Nges}}{G_A} \; ; \; S_{o_{ges}}^{RTW} \; ; \; G_A\right) \qquad\qquad (12)$$

The total installed gross stand thrust of the lift and cruise engines,
relative to the take-off weight S_{oges}/G_A, is also given in Figure 4 for the
parameter (μ_{HTW}, μ_{RTW}) which is primarily discussed here and for these con-
figurations.

Summary

In summary, based on the dimensioning of engines, it may be stated that
the horizontal and vertical force balance in transition and thus in the trans-
ition characteristics, are affected by the following design values of the
lift and cruise engines:

Direct by In- and Output Pulse Forces:

  the by-pass ratio of the lift and cruise engines;

  the thrust vector rotation of the lift and cruise engines.

Indirectly by the Dimensions of the Engines:

the by-pass ratio of cruise engines;

the cruise altitude and Mach number;

the number of lift and cruise engines.

4. Definition of the Reference Aircraft and Engine Parameters

4.1. Aircraft Configuration

As an example of a VTOL aircraft with a mixed lift configuration, a design was chosen in which the lift and cruise engines are arranged in wing gondola and where the thrust vectors are rotatable (Figure 5: Mixed lift).

The direct lift configuration of Figure 5 represents an alternative solution; here, only the lift engines are used to produce the lift thrust and the cruise engines are installed on the tail of the aircraft.

Mixed lift configuration
Cruise engine thrust vectors
fully rotatable

Direct lift configuration
Cruise engine thrust vectors
not rotatable
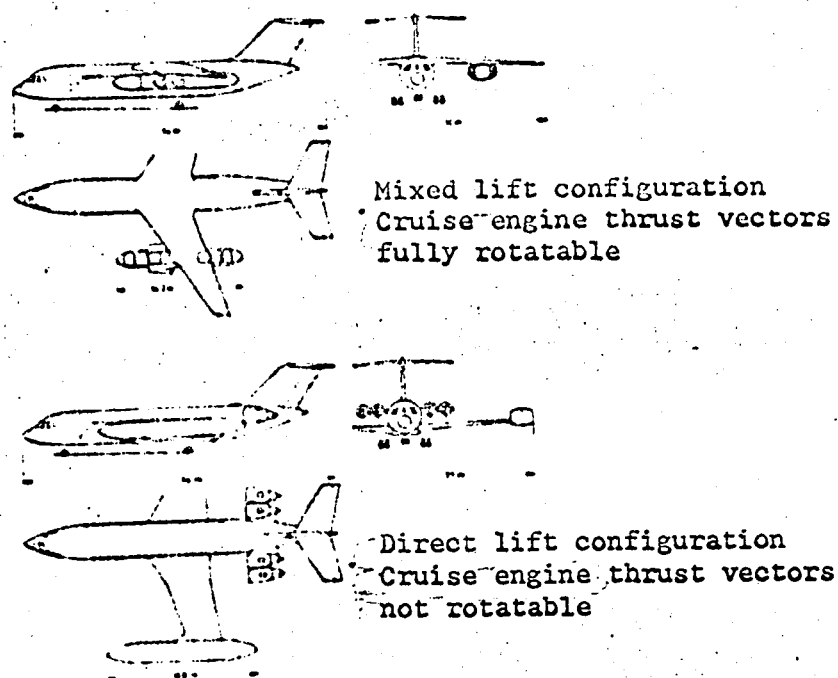
Design: take-off weight
         pay load
         range

Figure 5. Reference Aircraft
           Mixed and Direct Lift Configurations

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The fundamental design of the aircraft was based on the following data:

Take-off weight	G_A	=	52 $\cdot$
Payload	G_N	=	10 $\cdot$
Range	R	=	800 km
Cruise altitude	H_R	=	7500 m
Cruise Mach number	M_R	=	0.8
Wing load	G_A/F	=	400 kp/m^2
Wing spread	Λ	=	7
Slotted flap, flap angle	η_K	=	30°
Number of cruise engines	n_{RTW}	=	4
Number of lift engines	n_{HTW}	=	12
By-pass ratio of cruise engines	μ_{RTW}	=	6
By-pass ratio of lift engines	μ_{HTW}	=	10
Vertical take-off at	ISA, S. L.		
Status of engine technology	1975/1980		

As the deflection system of the cruise engines in the mixed lift configuration, Rolls-Royce rotatable nozzle deflector were chosen (2 jets on one side), while for the lift engines jet deflection with tiltable louvers by General Electric was selected; here the thrust vector of the lift engines can be rotated by a maximum value of E_{max} = 40° (Installation angle of lift engines = 0) [3].

4.2. Engines

The lift and cruise engines used in the present investigation are based on the assumed technology of 1975-1980. Corresponding to that stage of development, thermodynamic performance and condition data, weights and dimensions are used as calculated or estimated in the study "Parametric Engine Data" [3]. The structural types, assumptions and methods of computation used, especially the noise characteristics, are discussed in detail in [4]. The investigation of transition behavior is based on the following engine design:

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4.2.1. By-Pass Ratio

The lift and cruise engines considered in the present study are varied within a by-pass ratio range of 0 - 10.

4.2.2. Turbine Temperature

In accordance with the stand of technology chosen, all of the engines were designed for a turbine temperature of $T_{40} = 1573^{\circ}K$, which corresponds to maximum take-off performance and which is applied normally for a period of 5 minutes. In order to attain long durability, lower turbine temperatures are used during lift and cruise flight; here $T_{4St} = 1523^{\circ}K$ during the rise and $T_{4R} = 1473^{\circ}K$ during the cruise. The latter represents the standard long-time performance which can be applied without limitation.

4.2.3. Condenser-Total Pressure Ratio

On the stand, the following values were determined for this ratio:

cruise engines	$\pi_{30} = 18$
lift engines	$\pi_{30} = 8$

The pressure ratio of the cruise engines was set relatively low with $\pi_{30} = 18$, because in operation over short distances low engine weights are at least as important as the reduction of fuel consumption through higher pressure ratios.

The pressure ratio of lift engines was established at a higher value, $\pi_{30} = 8$, at the turbine temperature chosen, than used in existing life engines, in order to achieve high specific thrusts. In addition, this compensates the trend toward higher fuel consumption caused by the high turbine temperatures. The choice of even higher pressure ratios is limited by the need for light engine weights.

4.2.4. Fan-Pressure Ratio

The fan-pressure ratio is correlated with the existing by-pass ratio and the other design parameters (π_{30}, T_{40}) so that the specific fuel consumption is kept at a minimum. Correlation with maximum specific thrusts ($S_o/\dot{G}_H$) leads practically to the same result.

5. Effect of Lift and Cruise Engine Design on Transition Characteristics

In the following sections the effect of the parameters on transition behavior at a transition altitude of 150 m is investigated with respect to the configurations chosen; here, the dimensions of the engines in accordance with 3.2 and 3.4 was decisive for the thrust balance. In order to demonstrate the effect of the different design parameters, initially the transition characteristics at low deflection angles ϵ_{max} were determined.

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5.1. Transition at Low Lift Engine Deflection Angles

5.1.1. Wing Loads and Flap System

As shown by the results for transition time, fuel consumption and distance in Figure 6, these values rise very strongly with increasing wing loads, because with increasing G_A/F the aerodynamic ability to fly is attained at higher velocities v_{aero} only. At the initially assumed low angles of deflection of the lift engines the simple slotted flaps considered here are capable of reducing the minimum aerodynamic velocities so that the lift engines can be stopped sooner. The investigation showed that especially with high wing loads, which are favorable for VTOL aircraft, and an optimum flap angle of approximately 30°, substantial improvements can be achieved with respect to transition characteristics. Higher flap deflections lead to an increase in resistance which cannot be compensated by the increased lifting power; poorer transitions thus result.

5.1.2. The By-Pass Ratio of Lift and Cruise Engines

For the investigation represented in Figure 7, lift and cruise engines were varied for a fixed lift configuration over the entire range of by-pass ratios.

As may be expected from the horizontal force equilibrium, transition time and distance increase with rising by-pass ratios, because at the low deflection angle ϵ_{max} = 20° the inlet pulse force of the lift engines rises faster than the horizontal component of the output pulse force. Due to the substantially lower fuel consumption of the lift engines with high by-pass ratios, these also yield the lowest consumption in transition. Since the

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stand thrust of the cruise engines [as seen from Equation (4)], increases with the by-pass ratio and this, in accordance with Equation (11), in a mixed lift configuration the installed lift thrust decreases, transition characteristics improve with increasing μ_{RTW}.
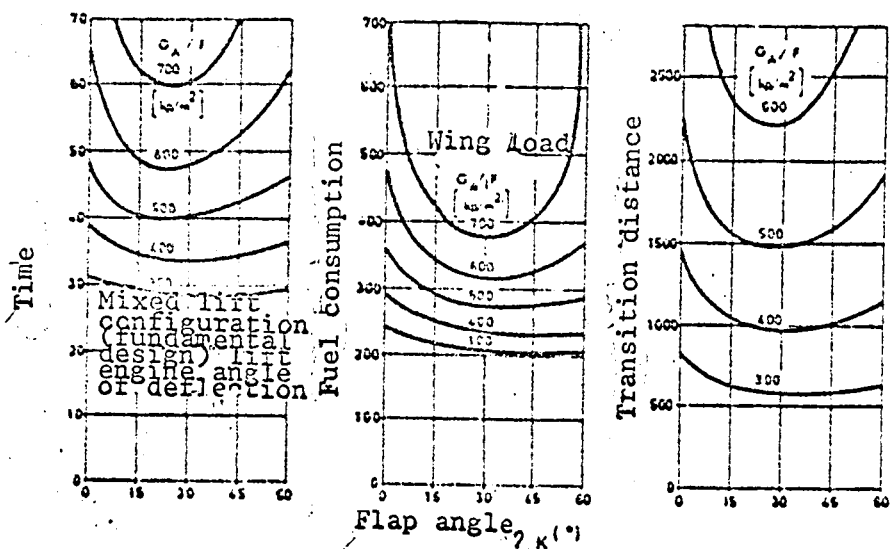

Figure 6. Effect of the Aerodynamics of the Wings Wing loads and flap angles with low values of ϵ_{max}.
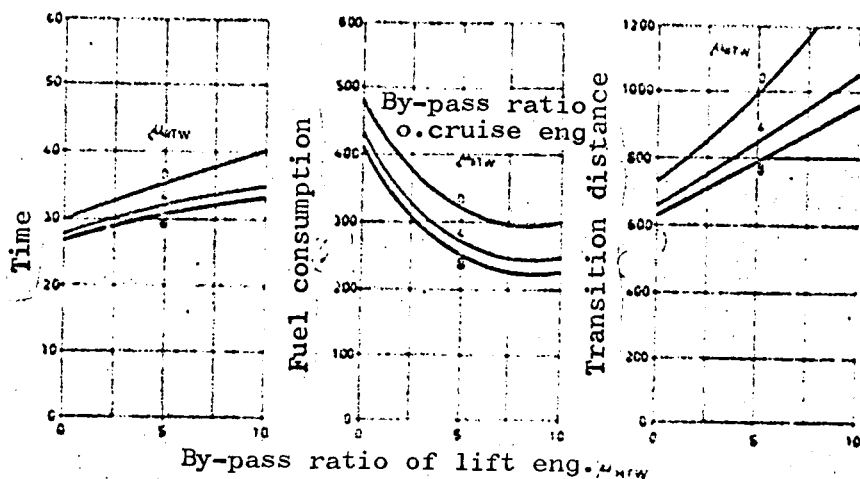

Figure 7. By-Pass Ratio of Effects Variation of Lift and Cruise Engines

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In summary, it may be stated that improvements of transition behavior can be obtained for the case of <u>low angles of rotation</u> of the lift engines with

    high by-pass ratios of cruise engines;

    low by-pass ratios of lift engines (i.e., low inlet pulse force) with respect to transition time and distance;

    low wing loads;

    medium flap angles of approximately 30°.

It should be particularly noted, however, that conditions of low wing loads and low by-pass ratios cannot be reconciled with optimum VTOL designs.

5.2. <u>Transition at High Lift Engine Deflection Angles</u>

As indicated above, the <u>horizontal</u> component of the lift engine outlet pulse force is of decisive importance with respect to the acceleration of the aircraft in transition. If it is possible to utilize the installed lift thrust to a greater degree through the use of suitable deflectors for horizontal acceleration, transition can be improved substantially and the detrimental effect of large lift engine by-pass ratios eliminated.

Figure 8 shows the transition time, consumption and distance as a function of maximum lift engine deflection angles for mixed and direct lift configurations. It is seen that regardless of the configuration or the by-pass ratio selected, deflection angles of at least 30° are required in order to assure optimum transition behavior and to eliminate the detrimental effect of large lift engine by-pass ratios described in Section 5.1.

For deflection angles of $\epsilon_{max} \geq 30°$, Figure 9, in comparison to Figures 6 and 7, demonstrate the small effect of the choice of wing load, flap angle and by-pass ratio of the cruise engines in transition performance.

In addition, Figure 8 compares mixed lift and direct lift configurations. It is shown that with low lift engine deflection angles the mixed lift solution is nearly always better, because due to the greater installed lift thrusts of the direct lift configuration (see Figure 4), the higher inlet pulse resistance of the latter cannot be compensated by the horizontal component of the outlet pulse force. However, in the case of greater angles of deflection,

the higher total thrust of the lift engines of the direct lift configuration
has a positive effect and transition becomes more favorable than with the
mixed lift configuration.

a. Mixed lift configuration (fundamental design)
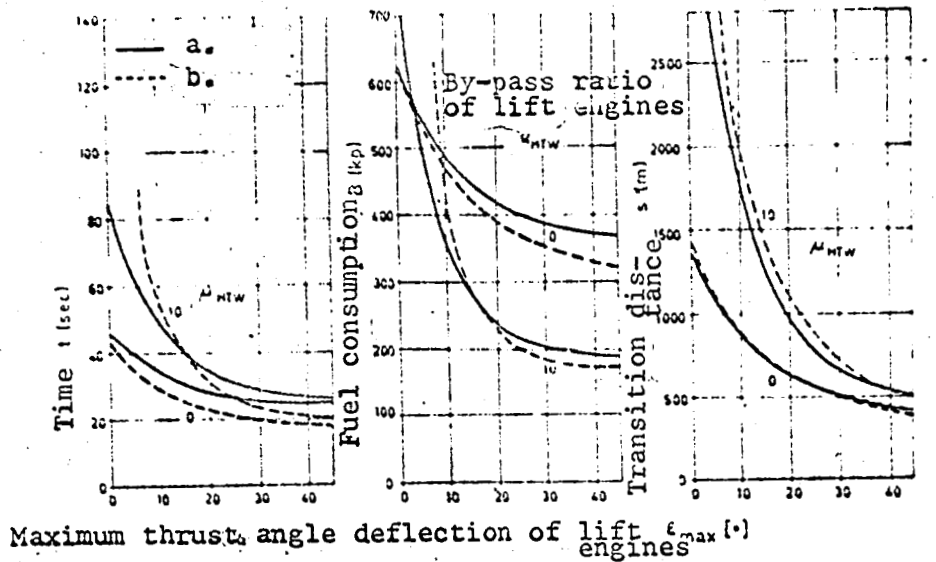b. Direct lift configuration (fundamental design)

Figure 8. - Effect of Thrust Vector Rotation of Lift
Engines

Mixed lift configuration (fundamental design)
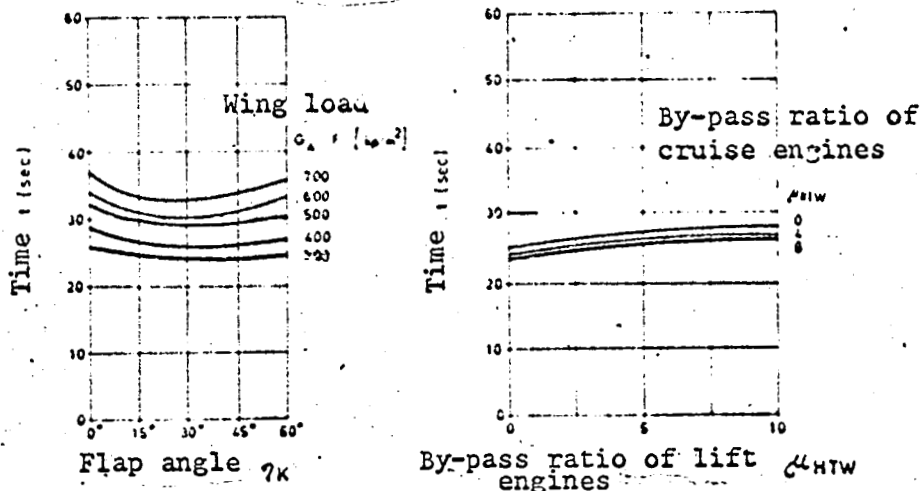Lift engine deflection angle $\varepsilon_{max} = 40°$

Figure 9. Effect of the Aerodynamics of the Wings and
the By-Pass Ratio at High ε_{max}

It is also seen that in spite of the high total thrust of the lift engines, the direct lift configuration does not attain the transition velocity at angles of rotation less than 10°, due to the high inlet pulse forces.

5.3. Engine Failure

For reasons of safety, it is necessary that following the failure of an engine and the potential shut-down of an engine symmetrically arranged with respect to the failed engine, at least the hovering capability or a net thrust excess $\Delta S_N'/G_A > 0$ should be retained. In addition, in accordance with FAA licencing regulations, it is required that the failure of an engine should not alter the configuration and that, therefore, the transition must be completed without the failed engine.

In order to analyze the effect of engine design parameters on transition behavior with a failed engine, a critical case in the form of an engine failure with a necessary stoppage of the symmetrical engine at the beinning of the transition was considered.

5.3.1. Failure of a Lift Engine

In the investigation of the failure of a lift engine at the start of the transition times, consumption and distances were determined as a function of the number of lift engines and presented in Figure 10 for mixed and direct lift configurations, with respect to the transition performances without lift engine failure.

a. Mixed lift configuration (fundamental design)
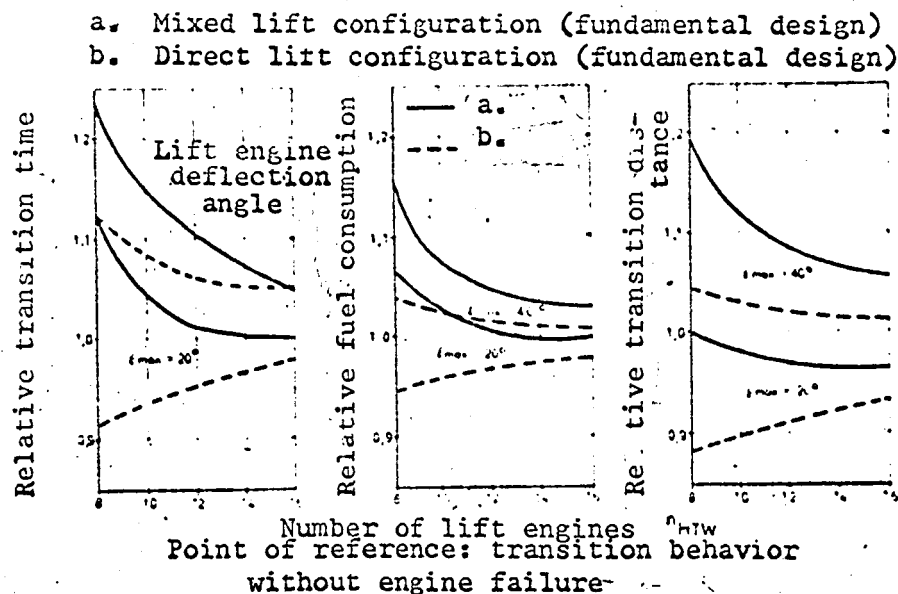b. Direct lift configuration (fundamental design)

Figure 10. Transition with a Failed Lift Engine
Failure and Shut-Off of Symmetrical Engine at the Start of Transition

The net excess thrust is taken into consideration in each case by the predimensioning of the engines.

It is seen that even with a failed engine, direct lift configurations, due to their substantially higher installed lift thrust, yield better transition performance than mixed lift configurations at an angle of deflection of $\epsilon_{max} \geq 20^o$.

With respect to transition characteristics without engine failure, however, time, distance and fuel consumption, even with high deflection angles $\epsilon_{max} = 40^o$, are higher by 10 to 20%, in both configurations. The same is true, with a low angle of deflection $\epsilon_{max} = 20^o$, for the mixed lift configuration.

In contrast to the foregoing, for direct lift configurations at <u>low</u> angles of deflection, transition characteristics improve following the failure of a lift engine with respect to the reference point, because at low deflection angles the inlet pulse force of the lift engines chosen here with $\mu_{HTW} = 10$, are higher than the available horizontal component of the output pulse force so that the failure or shut-off of lift engines in this special case improves the balance of forces and makes possible a somewhat higher acceleration.

In all cases, in spite of the failure of lift engines and symmetrical shut-off the transition and velocity is reached safely.

5.3.2. Cruise Engine Failure

The failure of a cruise engine was investigated for the configurations under study here (four cruise engines) as a function of the by-pass ratio μ_{RTW}, because with rising by-pass ratios of the cruise engines the thrust available for horizontal acceleration increases [Equation (4) and Figure 3].

$\epsilon_{max} = 40^o$:

As shown by the result of the investigation in Figure 11, with high angles of deflection of the lift engines $\epsilon_{max} = 40^o$, the failure of a cruise engine does not cause problems and leads, as compared with the results obtained without engine failure (Figure 9), to an increase in transition time of approximately 20% and of the transition distance of approximately 40%. In this

case, the direct lift configuration, even if a symmetrical engine is also shut off, yields better results. Since a suitable design of yaw control permits the elimination of symmetrical shut-offs in direct lift configurations, transition characteristics, as shown in Figure 11, are substantially better than in the mixed lift configuration.
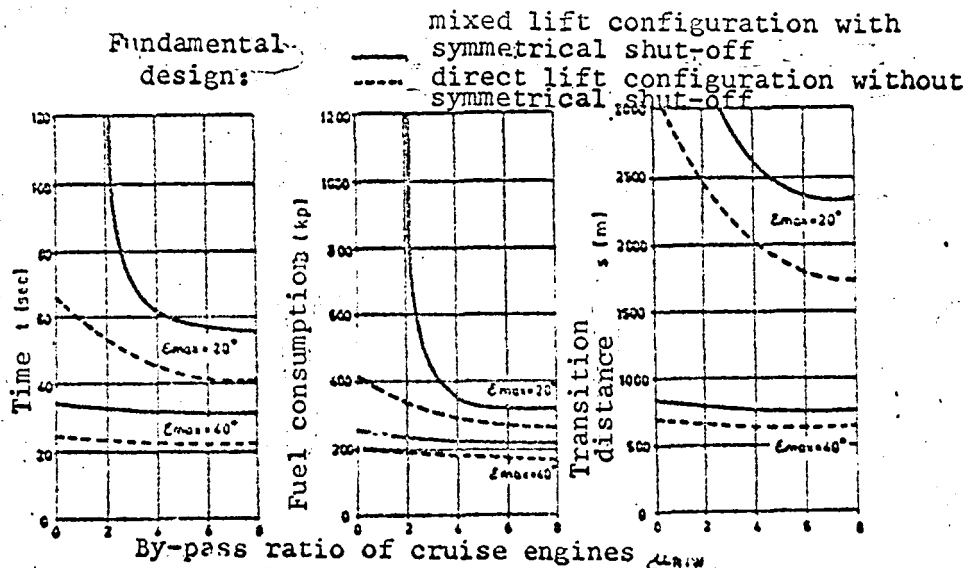

Figure 11. Transition with Cruise Engine Failure
Failure and potential symmetrical shut-off at the start of transition

$\epsilon_{max} = 20°$:

In the case of low lift engine deflection angles and small by-pass ratios of the cruise engines ($\mu_{RTW} < 3$), on the other hand, the mixed lift configuration is not capable of attaining the final transition velocity, following the failure of a cruise engine and the necessary symmetrical shut-off of another, because due to the missing thrust the horizontal acceleration is too low.

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In the case of a symmetry shut-off, direct lift configurations and for ϵ_{max} - 20° even with a high thrust proportion of the cruise engines, are not capable of completing the transition over the entire range investigated, because here again the inlet pulse force of the lift engines is greater than the horizontal component of the output pulse force.

If, however, the symmetrical shut-off of a cruise engine can be eliminated, the result presented in Figure 11 indicates that direct lift configurations are able to complete the transition even in the case of low lift engine angles and high by-pass ratios.

6. Transition with Variable Flight Paths and Constant Flight Attitudes and Engine Rotation Angle

Since, in order to parametrically investigate the effect of engines on transition an optimally unambiguous correlation of the determining factors, such as engine rotation angle, attitude angle, vertical acceleration and velocity had to be found, initially as a permissible simplification, in accordance with Section 2, transition at constant altitudes was considered.

In reality, however, a vertical velocity and possibly an acceleration component will have to be considered during the transition.

In addition, during the execution of the transition flight, it would be difficult for the pilot to monitor, together with the conventional instruments, three additional settings, i.e., the engine rotation angle σ and ϵ and the flight attitude angle ϑ . For this reason, the following investigations are based on a transition process which takes into consideration the foregoing and thus better satisfies the actual conditions; it loses, however, some of its flexibility with respect to the engine parameters.

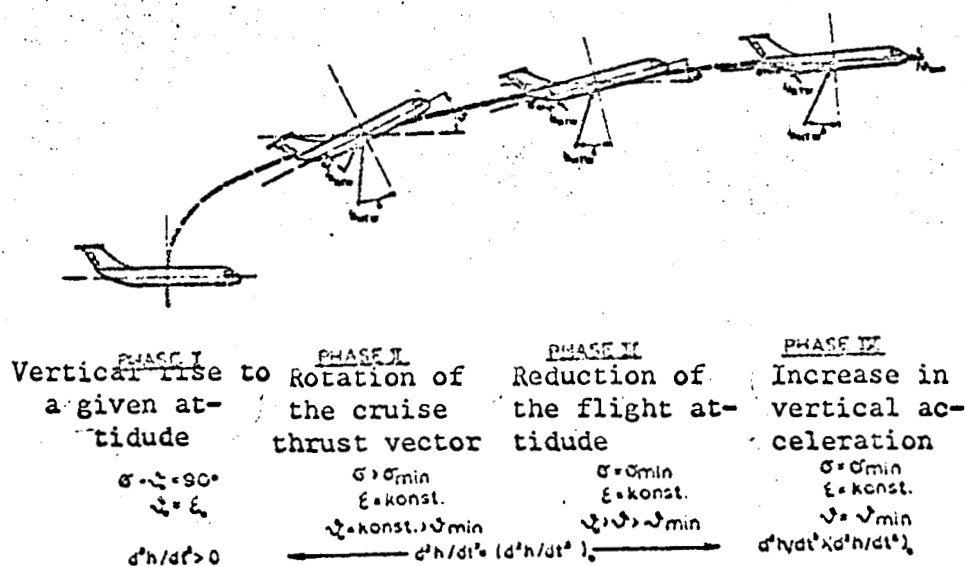| PHASE I	PHASE II	PHASE III	PHASE IV
Vertical rise to a given attidude	Rotation of the cruise thrust vector	Reduction of the flight attidude	Increase in vertical acceleration
$\sigma \lesssim 90°$	$\sigma > \sigma_{min}$	$\sigma = \sigma_{min}$	$\sigma = \sigma_{min}$
$\vartheta = \epsilon$	$\epsilon = konst.$	$\epsilon = konst.$	$\epsilon = konst.$
	$\vartheta = konst. > \vartheta_{min}$	$\vartheta > \vartheta > \vartheta_{min}$	$\vartheta = \vartheta_{min}$
$d^2h/dt^2 > 0$	$d^2h/dt^2 = (d^2h/dt^2)$		$d^2h/dt^2 \times d^2h/dt^2$

Figure 12. Transition with a Variable Flight Path Constant Flight Attitude and Engine Rotation Angles

The entire process from the start to aerodynamical flight is performed in the following phases (Figure 12):

Phase I   Vertical rise to a given altitude.

Phase II   With a constant given flight attitude angle ϑ and lift engine
           rotation angle ϵ and the vertical acceleration d^2h/dt^2 = constant,
           the corresponding angle of rotation of the cruise engines σ is
           determined in accordance with the equation of vertical motion,
           for the given, gradually varying flight velocity.

Phase III After σ_{min} is reached, the flight attitude angle ϑ is varied to
           a minimum value in accordance with the vertical force equilibrium.

Phase IV   The initial condition of a constant vertical acceleration is aban-
           doned for the case of $\sigma = \sigma_{min}$ and $\vartheta = \vartheta_{min}$ and the acceleration
           determined in accordance with the vertical equation of motion.
           The aircraft rises at a greater rate than in Phases II and III.
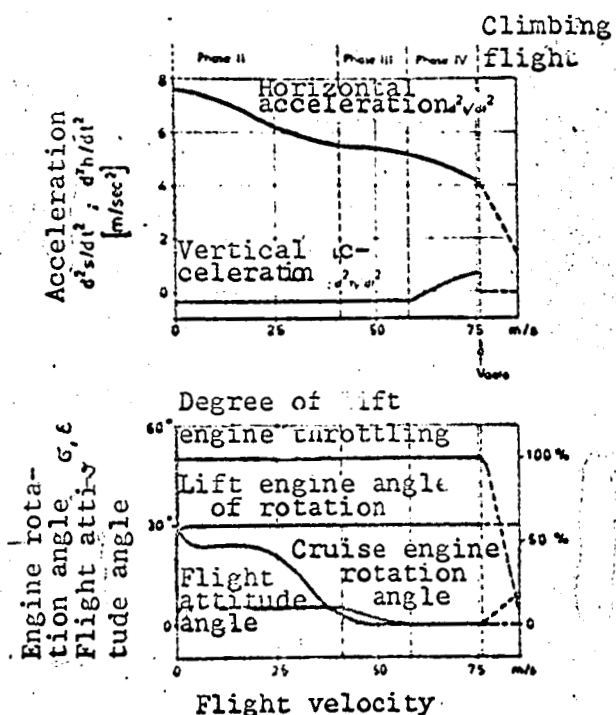   The lift engines are not throttled.

Figure 13.   Transition Process
             Transition-variable flight path

In Phases II to IV (Figure 13), the variation of σ and ϑ and the verti-
cal and horizontal acceleration is determined for the gradually varying flight
velocity v_∞, from these the instantaneous flight data and the transition time,
fuel consumption and distance may be calculated [2].

The transition is completed with the attainment of safe minimum aerodynamic velocity:

$$V_{aero} = 1.2 \cdot V_{min}$$

A comparison of the two transition processes considered here indicates (Figure 4) that the results of the parametric calculation at a constant transition altitude versus a flight profile with rising altitudes differ relatively slightly, particularly with respect to transition distance, and that deviations concerning transition time and fuel consumption appear to be permissible within the range of parametric engine investigations.
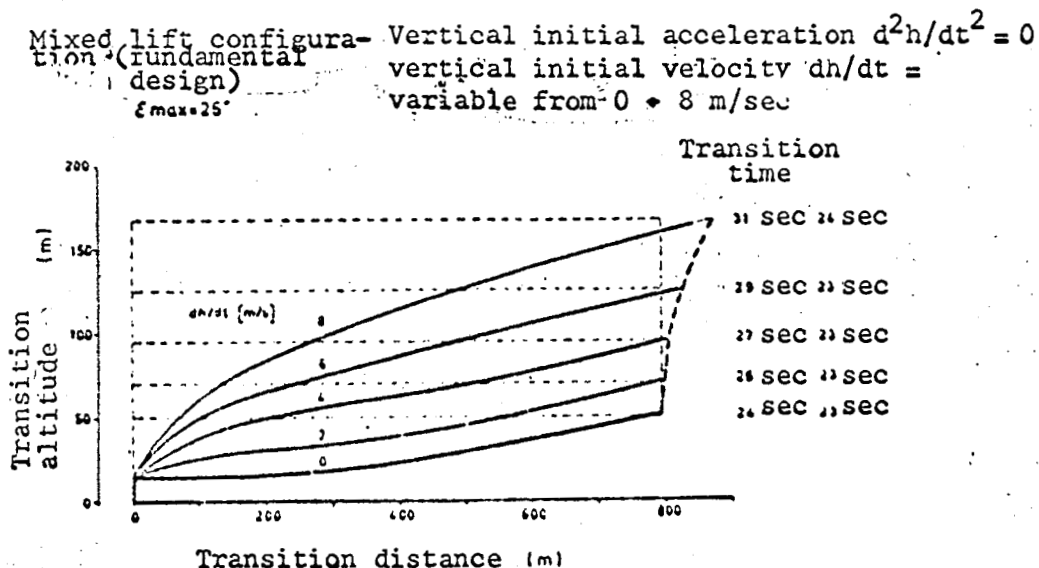
Figure 14. Comparison of Transition Processes
Flight path of constant and variable
transition altitude

In the following investigations to determine the acoustic ground field, reference is made to the transition processes described in the foregoing.

7. Transition with Minimum Noise

7.1. Conditions of the Determination of the Far Acoustic Field

Because VTOL aircraft are destined to take off and land in the immediate vicinity of cities or even in the center of cities, substantially more severe licensing regulations than those contained in Part 36 for HTOL aircraft must be expected. For this reason, as generally recognized, the choice of engines with respect to minimum noise grows increasingly important.

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a. Cruise engines
b. Lift engines

	a	b
Production	o	o
Prototypes	▲	△
Planned	■	□

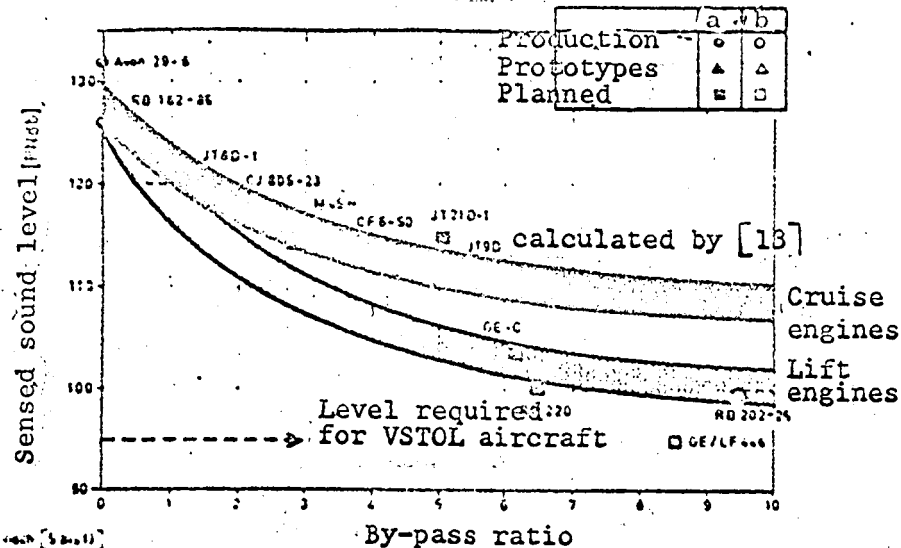Figure 15. Sound Level of Lift and Cruise Engines
-500 ft lateral distance

Figure 15 shows the sound level of lift and cruise engines currently built or planned at a lateral distance of 500 feet [5 to 13]. It is seen that although the development of engines with high by-pass ratios will lead to substantial reductions in the sound level for individual engines, the limit of 95 PNdb at a distance of 500 feet for VSTOL aircraft specified in German, British and American specifications cannot be obtained in the foreseeable future, because of the high thrusts to be installed.

Maximum sound levels on the ground for the mixed and direct lift configurations considered here (take-off weight approximately 62 t) were determined with consideration of the curves given in Figure 15 for the lift and cruise engines at a lateral distance of 500 feet as 108 and 102 PNdb (Figure 16). It was found that the specified sound level of 95 PNdb cannot be attained at this time with the entire VSTOL system and the engines planned, and that the throttling of the noise-intensive cruise engines in direct lift configurations permits a reduction in the noise level by approximately 6 PNdb.

Decisive reductions primarily in the acoustic ground field along the flight path thus are possible only through the choice of suitable transition processes.

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7.2. Effect of Transition Altitude on Acoustic Ground Field

The sensible sound level of an engine is a function, in addition to the engine characteristics and the thrust, primarily of the distance to the source of sound, so that a reduction of noise exceeding measures involving the engine can be obtained only by increasing the distance to the source of the noise.

Consistent application of the vertical take-off technique, i.e., by climbing vertically to greater transition altitudes makes it possible to:

concentrate the unavoidable noise nuisance upon lift-off at the immediate vicinity of the take-off location, and

execute subsequent jet-supported and aerodynamical flight at altitudes which permit the satisfaction of noise specifications on the ground.

Figure 17 demonstrates for a mixed lift configuration the effect of the initial transition altitude on the sound level on the ground, time, fuel consumption and the distance covered above the ground at the end of the transition.
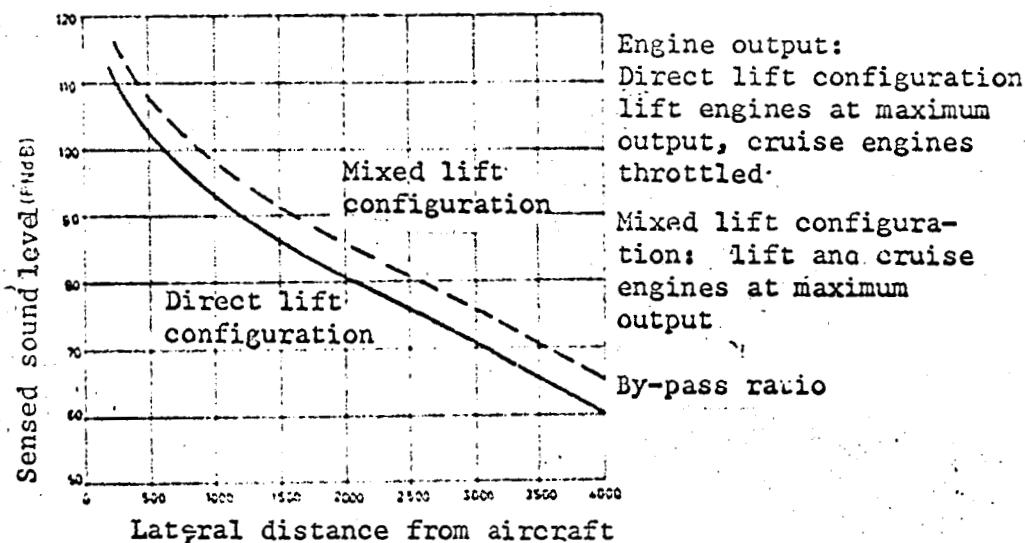

Engine output:
Direct lift configuration lift engines at maximum output, cruise engines throttled·

Mixed lift configuration: lift and cruise engines at maximum output

By-pass ratio

Figure 16. Maximum Sound Level on the Ground
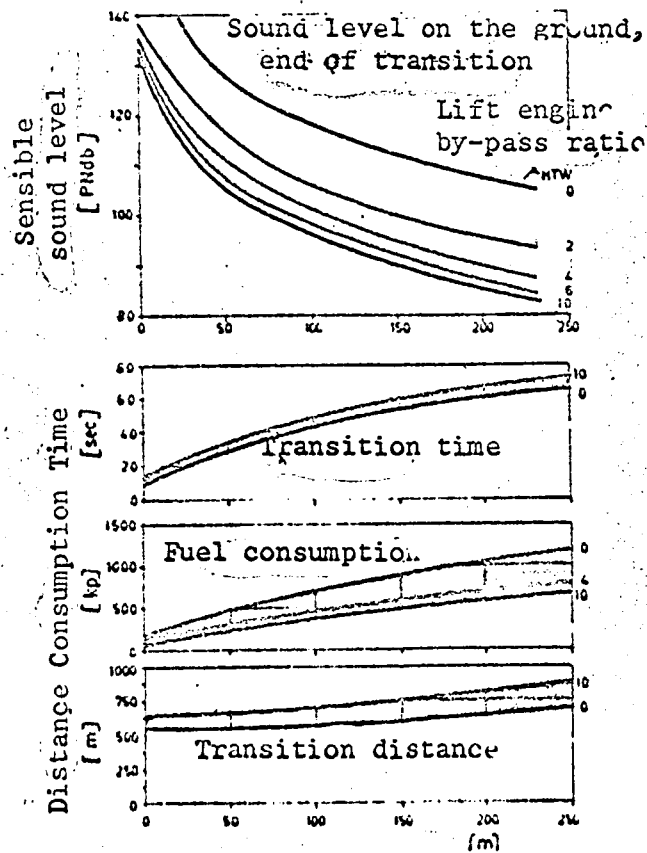— Hovering altitude 15 m, without ground effect

Figure 17. Effect of Transition Altitude
- Mixed-lift configuration -

In addition, the effect of different lift engines are investigated; the by-pass ratio of the cruise engines remained constant (μ_{RTW} = 6). It is seen that a given sound level may be attained under certain conditions with low values of μ_{HTW} by chosing high initial transition altitudes.

With increasing initial transition altitudes, however, time and fuel consumption rise substantially; this is due primarily to the prolonged vertical climbing phase, leading to increased direct operating costs (Section 7.4.). The transition distance is only slightly affected by the transition altitude; high by-pass ratios of the lift engines reduce mainly the fuel consumption to the end of the transition.

The effect of the initial transition altitude on the extent of the acoustic ground field is presented in Figure 18. As a comparison, for the mixed lift configuration a transition profile in ground vicinity (initial transition altitude 15 m, initial vertical velocity 8 m/sec) was confronted with a profile for a minimum acoustic ground field (with an initial altitude of 250 m, vertical initial velocity of 17 m/s).

Due to the different vertical velocities at the end of the climb phase, which are decisive with respect to the transition, a relatively flat flight path correlates with the low initial transition altitude and a steeper one with the high altitude.

With respect to permissible noise limits on the ground, for the determination of the initial transition altitude, the minimum acoustical ground field was defined as follows:

For a permissible limiting value of, e.g., 95 PNdb, the minimum lateral extent of the isobar is determined by the sound level generated immediately upon vertical lift-off (Figure 16) and which, therefore, cannot be affected any longer by the choice of the transition profile. The initial transition altitude must then be selected so that the lateral extent of the sound isobar is not exceeded.

In accordance with this assumption, for a minimum extent of the 95 PNdb isobar a transition profile with an initial altitude of 250 m was determined, which, based on the climbing flight path, leads to an acoustical ground field having an extent of only 800 m in diameter, and permits the limitation of the high sound level to the immediate area of the take-off location.

Mixed lift configuration
(fundamental design)
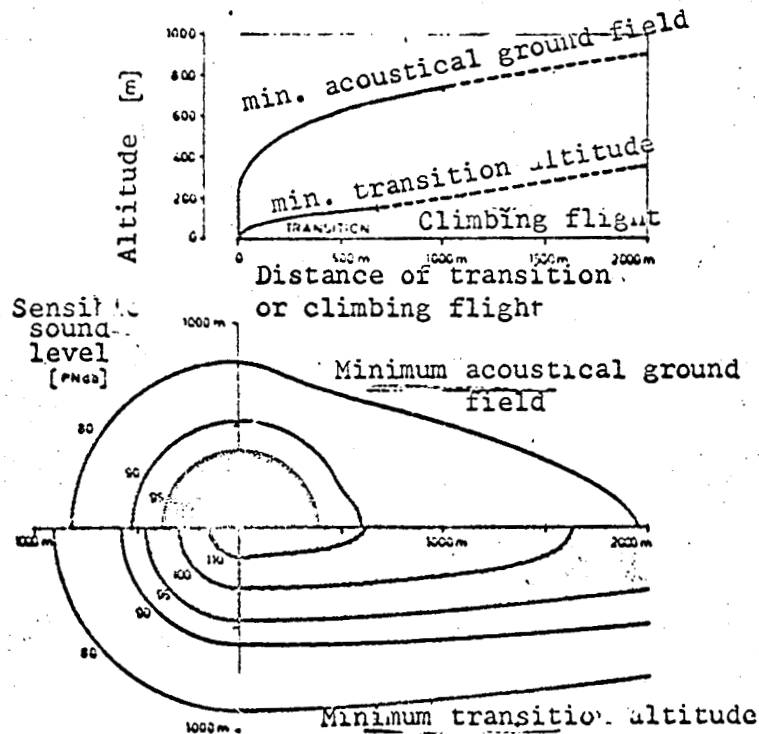$\varepsilon_{mol.} = 40°, \gamma = 10°$

Figure 18. Effect of Transition Altitude

In contrast, with a transition at low altitudes and subsequent flat climbing flights, a substantially greater expansion of the sound field (2400 m) of high intensity is unavoidable. The area irradiated with 95 PNdb is approximately four times the size of the minimum acoustical ground field at low transition altitudes.

7.3. Comparison of Mixed Lift and Direct Lift Configurations

With respect to transition performance, for high angles of deflection of the lift thrust, the superiority of the direct lift configuration has already been established (Section 5.2.). A comparison of minimum acoustical ground fields in Figure 19 in this example ($\mu_{RTW} = 6$; $\mu_{HTW} = 10$) also yields an advantage for the direct lift configuration, because the noise-intensive cruise engines can be throttled during vertical climbing. In accordance with Figure 16, the lateral extent of the 95 PNdb isobar is less, compared to the mixed lift configuration.

Fundamental design

$\varepsilon_{max} = 40° \quad \gamma = 10°$

Profile for minimum acoustical ground field
(95 PNdb)

Altitude [m]

TRANSITION — climb

Transition distance or climbing distance
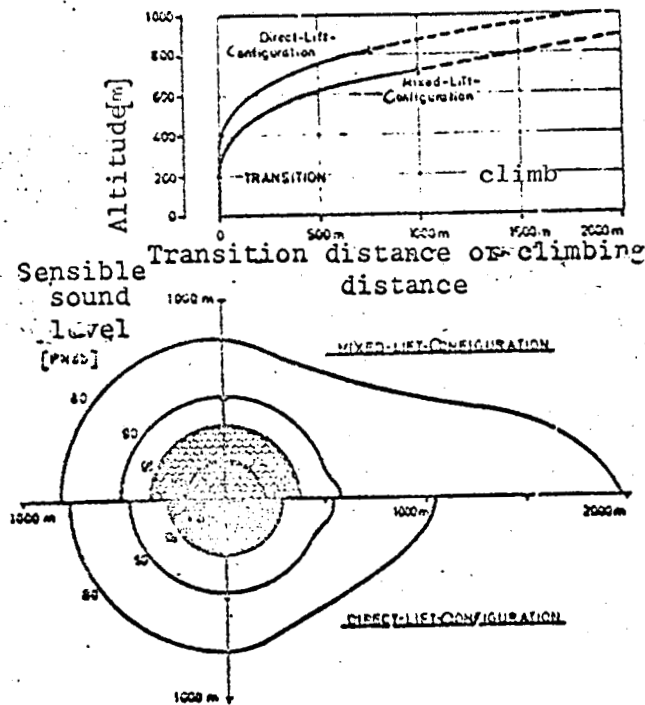
Sensible sound level [PNdb]

Figure 19, Comparison of Mixed Lift and
Direct Lift Configuration

Because during the take-off of a VTOL aircraft with a fully rotatable
cruise engine thrust vector (mixed lift configuration) the area irradiated
with more than 95 PNdb is unavoidably greater than if the noise-intensive
cruise engines are throttled (direct lift configuration), the resultant
initial transition altitude is approximately 250 m. In contrast, a greater
initial transition altitude of approximately 330 m is required for the direct
lift configuration, because at this point the cruise engines must be brought
to full capacity for the purpose of horizontal acceleration, thus lifting
the total sound level above that of the mixed lift configuration.

The acoustical ground field resulting from these transition profiles is
shown for the two comparative aircraft in Figure 19 and indicates that with
the engine technology on which the study is based a minimum extent of the
acoustical ground field at 95 PNdb of only 550 m in diameter can be attained,
coupled, however, with somewhat higher operating costs, due to the greater
initial transition altitude of approximately 330 m.

7.4. Effect of a Transition Optimum with Respect to Noise on Take-Off Weight and Direct Operating Costs

In order to estimate the effect of different initial transition altitudes on take-off weight and direct operating costs, the take-off weight and direct operating costs of the comparison aircraft were determined with the aid of an aircraft design program [1, 4] and not only the higher fuel consumption and the longer operating period of the lift engines considered as a function of the transition altitude, but also the reaction on the overall system in accordance with the magnifying factors observed.

In Figure 20, in accordance with the discussion of Section 7.2 and 7.3 the maximum extent of the acoustical ground field as a function of the initial transition altitude is shown, and the manner in which the initial altitude to be chosen depends on the permissible sound level on the ground and its maximum extension in the flight direction, is demonstrated.

It should be noted that following the completion of the transition, the lift engines are shut off and that thus the overall sound level of the aircraft decreases. This effect is not immediately obvious from the behavior of the curves for constant PNdb values, because here the decisive "peak noise level" is determined by the assumed acoustical field distribution of the cruise engines so that the shut-off of the lift engines in this special case leads merely to a negligibly small variation.

The take-off weight assigned to each initial transition altitude and the direct operating costs per seat-km are related to values for an altitude of 15 m. It is seen that even if a high transition altitude is chosen for a minimum acoustic ground field (95 PNdb), the take-off weight rises by only approximately 2.5%, which appears to be entirely acceptable with respect to the potential reduction of the noise trail. Direct operating costs, however, increase in this case by approximately 11% and thus attain orders of magnitude which in a genuine inter-city use of VSTOL aircraft will lead to cost increases. If, on the other hand, an extension of the permissible sound field in the flight direction is possible, then the additional cost as compared with transitions at low initial altitudes are substantially lower so that the amount of direct operating costs is affected decisively by legal noise requirements and by the location and size of the airport to be served.

Climbing flight

TRANSITION

Direct lift configura-
tion (fundamental design)

Altitude at the start of transition

[m]

[PNdb]

90

85

Take-off weight

Direct operat-
ing costs

Reference point

Maximum extent of the acou-
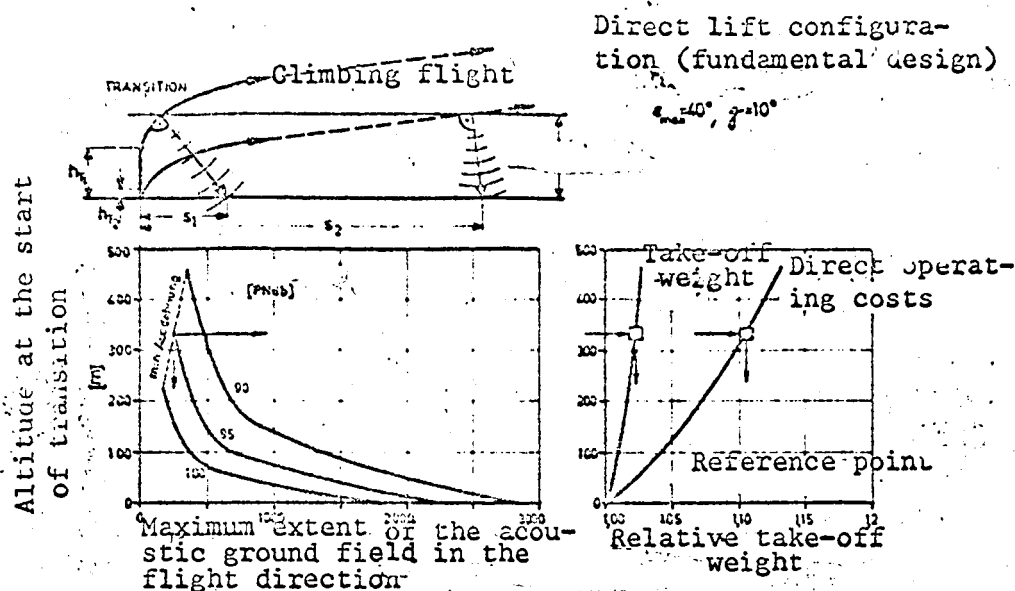stic ground field in the
flight direction

Relative take-off
weight

Figure 20. Effect of Transition Altitude on the Acoustic
Ground Field, Weight and Costs

8. Summary

It is shown through the dimensioning of lift and cruise engines and their
performance characteristics that the horizontal and vertical force balance in
the transition of vertically starting aircraft, and thus their transition
characteristics are decisively affected by the following engine design para-
meters:

directly by the ratio of the input-output forces, which rises with
the by-pass ratio of the lift and cruise engines;

also directly by the thrust vector rotation of the lift and cruise
engines which ermits an increase in horizontal acceleration with rising an-
gles of deflection;

indirectly by the optimum adaptation of cruise engines to cruise
flight requirements which leads with rising by-pass ratios, flight Mach num-
bers and altitudes to an increase in the cruise engine thrust available in
the transition, due to engine characteristics;

by the number of installed lift and cruise engines, which in the
case of engine failure and potentially necessary symmetrical engine shut-off
and a high number of engines leads to slight losses in thrust and thus im-
proved transition performance.

The results of the <u>parametric investigation</u> of engines for two comparison aircraft (mixed and direct lift configurations) confirmed the trends determined by the dimensioning of the engines. Important results are the following:

for the execution of safe transitions primarily <u>high angles of deflection</u> $\epsilon_{max} \geq 30°$ of the thrust vector of lift engines are required. In this case, necessary lift aids for the transition may be eliminated and the wing load and the design of cruise engines can be largely based on the optimum needs of the cruise and climbing flights. Direct lift configurations without rotation of the cruise thrust vector in this case yield better transition performance, due to higher installed lift engine thrusts. High by-pass ratios of the lift engines affect fuel consumption favorably in this phase, without -- at high lift engine deflections -- substantially reducing other transition characteristics;

if <u>low angles of rotation</u> are permissible only for the thrust vector of lift engines, the transition can be favorably influenced by the choice of low by-pass ratios for the lift engines, high by-pass ratios for the cruise engines, low wing loads and a flap system ($\eta_K \approx 30°$). Here again, mixed lift configurations with fully rotatable cruise engine thrusts are desirable.

The safe completion of the transition in the case of engine failures is, however, assured for mixed lift configurations only with cruise engines $\mu_{RTW} \geq 3$ and with direct lift configurations only if symmetrical shut-offs can be eliminated.

The requirement of an <u>acoustic ground field of minimum dimensions</u> (95 PNdb at a lateral distance of 500 feet) cannot be satisfied with vertical lift engines under development at the present time. It is, however, possible through consistent application of vertical lift technology, i.e., through vertical climbing to initial transition altitudes of approximately 300 m and the choice of suitable transition profiles to:

attain a concentration of the noise nuisance which is unavoidable at the present time in the immediate vicinity of the take-off location and

conduct the subsequent jet-supported and aerodynamical climbing flight at altitudes which minimize the dimensions of the area exposed to the highest permissible sound level of 95 PNdb.

The higher the transition altitudes which must be selected because of specified minimum dimensions of the acoustic ground field, the more primarily the direct operating costs will rise compared with those of transition profiles in ground vicinity. To attain a minimum acoustical ground field possible at this time (approximately 600 m diameter) of 95 PNdb, an initial transition altitude of approximately 300 m is required. The increase in costs compared with an initial altitude of 15 m is approximately 11%.

Engine design parameters for optimum transition performance and with respect to minimum acoustical ground fields are in agreement; due to the throttling of the noise-intensive cruise engines in the vertical phase, direct lift configurations yield lesser acoustical ground fields than mixed lift configurations.

9. Notation

Symbol	Units	Description
A	(kp)	Lifting power
ΔA_A	(kp)	Jet-induced drift
a_∞	(m/s)	Velocity of sound
B	(kp)	Fuel consumption
b_v	(m/sec.^{2})	Vertical acceleration
C_{AR}	(-)	Lift power coefficient in cruise flight
C_{WR}	(-)	Resistance coefficient in cruise flight
C_{Wo}	(-)	Zero resistance coefficient
dh/dt	(m/sec)	Vertical velocity
d^2h/dt^2	(m/sec^2)	Vertical acceleration
d^2s/dt^2	(m/sec^2)	Horizontal acceleration
DOC	(DPf/seat-km)	Direct operating costs per seat-km
F	(m^2)	Wing area
G_A	(t)	Take-off weight
G_A/F	(kp/m^2)	Wing load
G_N	(kp)	Payload
g	(m/sec^2)	Gravity acceleration
H_R	(m)	Cruise flight altitude

h	(m)	Altitude	/38
h_T	(m)	Initial transition altitude	
j_E	(kp)	Input pulse force	
j_A	(kp)	Output pulse force	
K_R	(-)	Installation losses in cruise flight (inlet pressure drop, air and power diversion, deflection loss)	
K_{HTW}	(-)	Installation loss of lift engines on the stand	/39
K_{RTW}	(-)	Installation losses of cruise engines on the stand	
M	(-)	Mach number	
n	(-)	Number of engines	
R	(km)	Range	
S_o	(kp)	Gross stand thrust of <u>one</u> engine	
S_N	(kp)	Net stand thrust of <u>one</u> engine	
S_x	(kp)	Thrust of a failed or shut-off engine	
$S_o/\dot{G}$	(sec)	Specific thrust	
ΔS_{Not}	(kp)	Emergency thrust reserve of an engine	
$\Delta S'/G_A$	(-)	Excess thrust after engine failure	
$(\Delta S/G_A)_{Steu}$	(-)	Loss of thrust due to control	
s	(m)	Transition distance over ground	
T_{40}	(^{o}K)	Turbine inlet temperature on stand	
T_{4St}	(^{o}K)	Turbine inlet temperature in climbing	
T_{4R}	(^{o}K)	Turbine inlet temperature in cruise flight	
t	(sec)	Time	
v	(m/s)	Velocity	
v_{aero}	(m/s)	Transition velocity	
v_{min}	(m/s)	Minimum aerodynamic flight velocity	
$\dot{v}_v$	(m/s)	Vertical velocity	

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W	(kp)	Resistance
ΔW_A	(kp)	Jet-induced resistance
z	(-)	Number of failed and shut-off engines
α	(°)	Angle of attack
$\bar{\gamma}$	(°)	Average angle of path in climbing
ϑ	(°)	Flight attitude angle
ϵ	(°)	Angle of rotation of the thrust vector of lift engines with respect to the longitudinal engine axis
η_K	(°)	Flap angle
Λ	(-)	Aspect ratio
μ	(-)	By-pass ratio
π_{30}	(-)	Compressor - total pressure ratio
ρ	(kp sec^2/m^4)	Density
σ	(°)	Angle of rotation of the thrust vector of cruise engines with respect to the longitudinal axis of the engine

/40

Indices

∞	Undisturbed flow
ges.	Total
HTW	Lift engine
RTW	Cruise engine
R	Cruise flight
Steu	Control by installed thrust
VTO	Vertical take-off

REFERENCES

1. Pakendorf, H., "System Analysis of Future Jet and Turbine Engines for Vertical Takeoff Traffic Aircraft" Dissertation, Department of Mechanics, Berlin Technical University, D 83, Berlin, 1969. /41

2. Brenneke, W., Benz, G., Bottger, G., "Takeoff and Landing Techniques of VSTOL Transport Aircraft Under Consideration of Potential Licensing Requirements with Given Noise Limitations," Project VFW 1.01, Vol. III in ZTL Program 1969. Contract No. T/0135/94100/92451 Unpublished Report, March, 1970.

3. Pakendorf, H., Sommers, C., "Parametric Engine Data," Technical Report VFW TB-Eft 12/67. Unpublished Report, January, 1968.

4. Pakendorf, H., Bottgen, G., "The Design of Engines for Vertical Takeoff Transport Aircraft," Technical Report VFW TB-Et 1/69 .

5. Hoch, R. and Duponchel, J. P., SNECMA, Paris, "Method of Estimating the Noise of a Turbine Engine from Its Thermal Propulsion Characteristics" Paper, AGARD Meeting, St. Louis, May 1969.

6. "RB 202 Lift Fan Noise Statement" Preliminary Design Memorandum, Rolls-Royce, PDM 32017, 1969.

7. "Preliminary Performance Specification and Installation Notes RB 220-02" Rolls-Royce, PPS 00019, 1969.

8. "Installed Engine Noise Levels Twin Wing Pylon-Mounted Applications" General Electric E-2098 A, April 1969. /42

9. "Static Noise Measurements of the RB 162-86 Engine" Installation Noise Report (NR 5400), Rolls-Royce, February, 1970.

10. "JT21D-1 Turbofan Engine Noise," Unpublished Report, Pratt and Whitney, 1970.

11. "System Noise Level Estimates," Unpublished Report, General Electric, December, 1969.

12. "M45 H Aston Down Noise Measurements," Unpublished Report, Rolls-Royce, January, 1970.

13. Jackson, H. A., "Introduction to the JT9D Engine," Pratt & Whitney.